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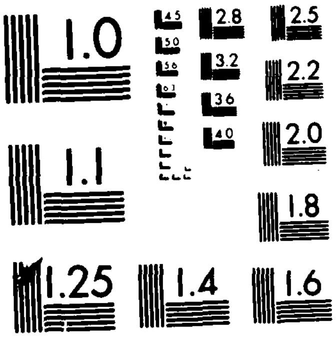
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ANOMALOUS LASER INDUCED BUNCH LENGTHENING ON THE ACO STORAGE RING FREE ELECTRON LASER*

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Abstract

Laser induced bunch lengthening has been measured on the ACO Storage Ring Free Electron Laser (SRFEL) in the anomalous bunch lengthening regime. The experimental results show correlations between the appearance of coherent modes in the electron bunch and anomalous behavior in the presence of the laser. Simultaneous time resolved laser induced bunch lengthening, mode strength, bunch length, and synchrotron sideband measurements were made as anomalous thresholds were traversed several times by changing the RF accelerating voltage. Bunch shortening, multiple time constants, and oscillatory behavior are among the phenomena which have been observed.

Introduction

During the investigation of laser induced electron bunch lengthening as part of the ACO Storage Ring Free Electron laser project we observed anomalous behavior which was indicative of thresholds. In order to correlate the appearance of coherent modes in the electron bunch with the observed behavior we have [illegible] the first two principal coherent mode thresholds at moderate current in order to explore in detail the nature of the anomalous coupling between the laser and the electron beam.

Our interest in this anomalous coupling is motivated by the role the laser induced bunch lengthening is believed to play in the output power saturation and efficiency of the SRFEL. Although we have observed agreement with the theory of the idealized SRFEL at low current[1] the coupling between the FEL interaction and the collective effects which give rise to anomalous bunch lengthening on storage rings has yet to be theoretically analyzed. Experimentally, it is clear that this coupling completely changes both the qualitative and quantitative nature of the response of the electrons to the FEL, completely dominating the interaction in ACO at moderate and high currents. It seems likely that these effects will dominate the operation of all SRFELs operated in the anomalous bunch lengthening regime.

Experimental Procedure

All of the measurements presented here were made at a mean electron energy of 237 MeV. The momentum compaction, α, was .028. The wiggler parameter was 1.922, and the peak laser intensity was approximately 200 watts/cm^2. The energy damping time of ACO at this energy is 65 msec. Additional information concerning the optical klystron used on ACO may be found in reference 2.

The measurements reported here used the frequency domain techniques developed for recording the time averaged response of the electron beam to the laser.[1] An additional AILTECH 757 RF spectrum analyzer was used to simultaneously measure the absolute bunch length and synchrotron sideband spectrum. The coherent modes were measured using a technique employed at SPEAR.[3] The output of an electrode chosen for high frequency response was sent through a high pass filter, a hot-corner Schottky diode, and analyzed using a low frequency spectrum analyzer.

After injecting the storage ring with a total average current of less than 1 mA average current, the anomalous threshold current, the external laser was aligned co-linear with the electron beam in the optical klystron. The magnetic field, alignment, laser peak intensity and chopping speed were optimized to obtain the maximum signal-to-noise ratio of the laser induced bunch lengthening. A chopping period of 2 sec was selected to increase the interaction time as much as possible without unduly lengthening the averaging time required to obtain a satisfactory signal-to-noise ratio. The storage ring was re-injected and alignment verified. The measurements were begun with about 3 mA of total average current in one electron bunch having a σ of 400 psec.

The RF accelerating voltage was scanned in both directions and at every point the following data was recorded: the time averaged laser induced bunch length change (32 scans @ 2 sec/scan), the absolute bunch length, the synchrotron sideband spectrum at 477 MHz, the 35th harmonic of the orbit frequency, the number of coherent modes present and their strength in decibels above the zero current noise level. The scans of the RF voltage were made in both increasing and decreasing directions to expose any hysteresis. Several scans were made until the current remaining from the normal lifetime decay of the electron beam was below the anolamous threshold at all peak RF voltages.

Figure 1 shows a few of the several different responses recorded as compared to a normal low current scan and the laser chopping phase. Figure 1(a) is a low current scan taken after optimization. The scan was taken just prior to the re-injection of the storage ring for the threshold measurements. It was taken with a total of .5 mA in the storage ring, and is scaled to a RF voltage of 11 kV. The normal exponential response is apparent. During the traversing of thresholds often the electron bunch would have no time averaged response to the external laser as shown by the trace in 1(b) taken at a current of 1.71 mA, an RF voltage of 9 kV, and a ξ of 0.40 amp/MeV (the turbulent scaling parameter see ref. 4). Figure 1(c) shows a 180° phase reversal of the signal indicating an induced shortening of bunch length. The signal is proportional to the inverse bunch length so that a higher signal amplitude represents a shorter bunch length. Figure 1(c) was taken at 1.56 mA, 11 kV peak RF, and a ξ of 0.30 amp/MeV. Figure 1(c) may be compared directly with 1(a). The induced signal compared directly with 1(a). The induced signal of 1(c) is approximately 5 times that of the equivalent low current signal, 1(a). Figure 1(d) taken at 1.4 mA, a ξ of 0.21 amp/MeV, and 15 kV Vrf. It shows some of the oscillatory behavior observed. Oscillations at twice and three times the chopping frequency were common and their period is much longer than the nominal energy damping time of the storage ring. Figure 1(e) at 2.04 mA, ξ of 0.32 amp/MeV, and 14 kV is an example of the damped oscillations that were observed. Figure 1(f) is the laser phase reference for the traces and the vertical scale of all the traces is identical.

Figure 2 compares the absolute value of the peak-to-peak laser induced bunch lengthening signal, the absolute bunch length, and the coherent dipole and quadrupole strengths as a function of the scaling parameter

$$\xi = I\alpha / E \nu_s^2$$

used in characterization of turbulent bunch lengthening.[4] I is the current stored, α the momentum compaction, E the electron energy, and ν_s the ratio of the synchrotron frequency to the orbit frequency. The measurements were made during one injection so that the mean energy and momentum compaction were constant. The solid points were taken with increasing RF voltage; the open faced points with decreasing voltage. The arrows on the figure point out some of the features of two of the major thresholds present. The arrows at the right of Figure 2 corresponding to a ξ of 0.65 amp/MeV show a coherent dipole transition and a corresponding change in the laser induced bunch modification signal. The arrows at the left at a ξ of 0.30 amp/MeV show a transition present in both the dipole and quadrupole coherent modes and a very large change in the bunch lengthening signal. An additional transition at a ξ of 0.52 amp/MeV is apparent in the bunch lengthening signal corresponding to the quadrupole mode transition at this point.

The scaling parameter ξ reveals thresholds present in the electron beam and large changes in the bunch lengthening signal, but it does not provide any classification of the types of induced bunch lengthening observed.

Summary

As is apparent in Figures 1 and 2, the appearance of the anomalous FEL bunch heating effects are strongly correlated with the presence of the coherent dipole and quadrupole modes. The anomalous coupling can give rise to electron bunch length changes which can be a factor 5 greater than the low current bunch lengthening measured under identical conditions. The qualitative response of the electron bunch changes completely. Induced changes in sign of the signal and oscillations at frequencies greater than that of the laser chopping are common. The existence of the turbulent and coherent bunch lengthening on ACO explains why the first attempts to measure the bunch lengthening were unsuccessful.[5] Our results suggest that the behavior of a storage ring FEL operated in the anomalous bunch lengthening regime will be dominated by the excitation, or de-excitation, of the coherent modes.

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We would like to thank the other members of the LURE/Stanford FEL group, C. Bazin, M. Bergher, M. Billardon, P. Elleaume, J. M. Ortega and Y. Petroff for their assistance during runs. We are also grateful for the assistance of the administrative and technical staffs of LURE and of the Laboratoire de l'Accélerateur Linéaire at Orsay, France, and AILTECH-France, a division of Eaton Corporation, for providing some of the equipment used for these measurements.

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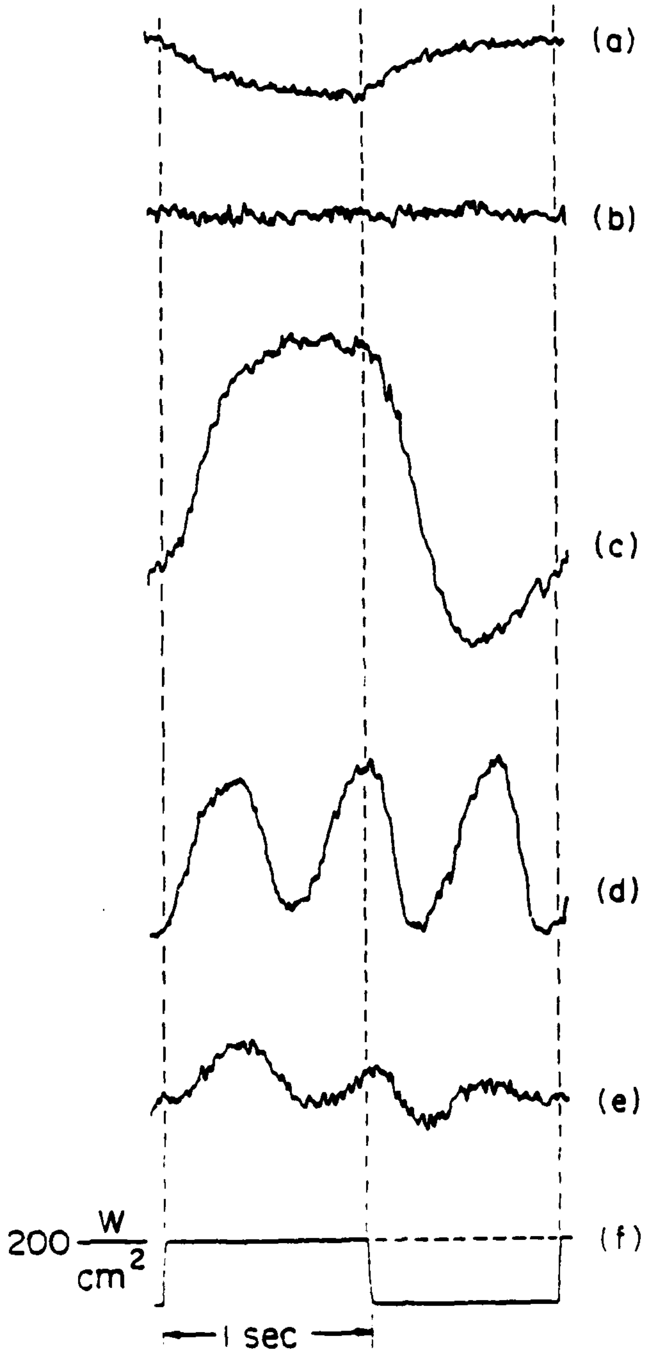

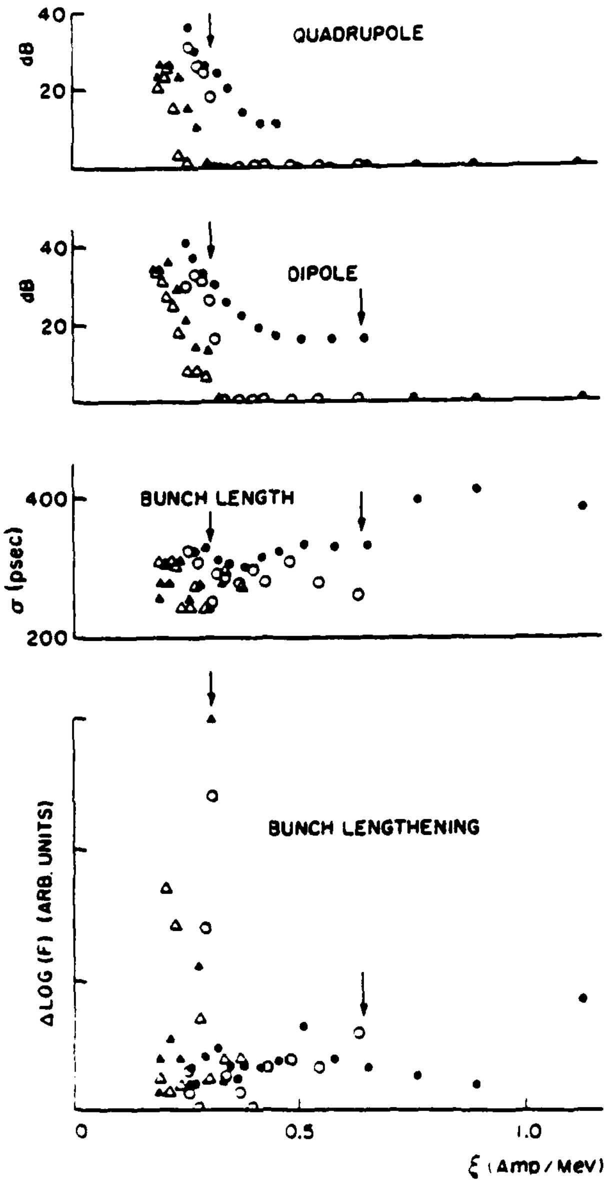

Figure 1: Representative sample of the time averaged laser induced bunch lengthening signals observed in the anomalous threshold regions. (a) Low current scan taken at 0.5 mA and scaled to 11 kV Vrf for comparison with the anomalous behavior. (b) Null signals observed at a current of 1.71 mA, Vrf of 9 kV, and ξ of 0.40 amp/MeV. (c) Bunch shortening signal observed at a current of 1.56 mA, 11 kV Vrf, and ξ of 0.30. (d) Oscillations observed at 1.40 mA, 15 kV and a ξ of 0.21 amp/MeV. (e) Damped oscillations observed at 2.04 mA, 14 kV Vrf, and ξ of 0.35 amp/MeV. (f) Laser chopping phase reference for (a) - (e). Traces (a) - (e) may be compared directly as the vertical scales are identical.

Figure 2: Plots the absolute value of the laser induced bunch lengthening, absolute bunch length, and the strengths of the dipole and quadrupole coherent modes as a function of the scaling parameter ξ. Arrows point out features of some of the thresholds observed.

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